DESIGN AND IMPLEMENTATION OF A GPS-BASED NAVIGATION SYSTEM FOR MICRO AIR VEHICLES

BY

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Micro air vehicles (MAVs) are becoming vastly popular in the areas of surveillance and reconnaissance for military and civilian use; however, their instability due to their small size renders them useful to only a handful of pilots. We propose implementing a GPS-based navigation system for use in autonomous flight of micro air vehicles. Previous efforts in this area have produced a vision-based horizon tracking algorithm capable of sustained level flight with user input. Our goal is to improve on this flight system using information from a GPS receiver. In this thesis we first introduce the current vision-based navigation system and discuss its limitations. We next discuss the proposed improvements to the navigation system through GPS. Then, we describe the design of the hardware system and software algorithms for navigation and control. The GPS- and vision-based navigation system has been successfully integrated and tested in multiple ground-based simulations at the University of Florida.

CHAPTER 1
INTRODUCTION

1.1 Micro Air Vehicles

Since the beginning of modern aviation the goal of research has been to produce larger faster winged vehicles. These designs have succeeded in pushing the envelope and creating superior passenger jets and fighter planes. Currently, however, efforts are emerging to tackle problems associated with designs derived from the other end of the spectrum. Small winged vehicles, or *Micro Air Vehicles* (MAVs), are being developed to participate in dozens of low-altitude surveillance missions not suitable for larger planes.

MAVs hold a great potential for use in the surveillance field. Equipped with small video cameras and transmitters, they can be used in areas too remote or dangerous for a human counterpart. Their small scale and low noise enables them to blend in with the sky and surroundings, rendering them unnoticeable. Even at low altitudes, their strong resemblance to insects and birds enables MAVs to operate unnoticed. This trait lends itself well to unobtrusive wildlife surveillance, as well as a variety of military applications.

MAVs will become an integral part of the battlefield, relaying real-time data to troops close by. They can be easily deployed by soldiers for short range reconnaissance work where battlefield information is to difficult or expensive to obtain quickly. This new capability will reduce casualties among military personal while improving intelligence data.

With the continuing trend in developing cheaper faster and smaller electronics, MAVs can be outfitted to serve a variety of monitoring missions in addition to general surveillance. Equipped with the proper sensors, MAVs can locate areas of high radiation, monitor chemical spills, perform forrest fire reconnaissance, monitor volcanic activity, and survey natural disaster areas. The new electronics can also be used to improve the navigation abilities of MAVs.

The small size requirements of MAVs generate a variety of challenges in development not seen in their larger wing counterparts. These challenges fall into three broad categories: (1) aerodynamic efficiency, (2) increased wing loading and (3) stability and control [4]. Solutions for the first and second challenges are currently being developed in the Micro Air Vehicle Laboratory at the University of Florida in the form of innovative designs incorporating advanced materials [6]. In this thesis we propose solving the third challenge of stability and control. We plan to implement a GPS-based navigation system into the existing vision-based navigation system to solve this challenge. The resulting flight control system will be capable of achieving fully autonomous flight, removing the human component from the control loop.

1.2 Navigation Systems

The current GPS constellation which began operation in the early 1990's allows for accurate land based navigation with meter accuracy [1]. This system is widely becoming the standard for land and air based navigation [9]. Within the United States, GPS has been approved as an IFR supplemental navigation system for domestic en route phases of flight, and as a primary means for oceanic navigation. [12].

Presently, GPS is being added to the primary computer systems of large aircraft, increasing their navigation abilities. We feel GPS can also greatly alter the usability of MAVs. The lack of stability and control inherent in MAVs renders them useful to only a handful of skilled pilots. With the proper navigation system, the MAVs can be telecontrolled by a computer, eliminating the major stability challenges of flight, and allowing any pilot to focus on altitude and direction. With a GPS-based navigation system, the pilot can be further removed from the control loop. This system could fully control the flight of the aircraft allowing any person to operate the MAVs by simply programming a flight path.

1.2.1 Ground Vehicles

Efforts have been made in implementing GPS-based navigation in ground-based mobile robots with additional sensors as done by M. Betke and K. Gurvits [3], and L. Lin et al. [8]. Ymanashi University developed a system to navigate outdoor terrain based on an environment model. The navigation system is based on differential GPS (DGPS), and can achieve accuracies down to 5m. The robot begins a mission with a predetermined course based on GPS coordinates or waypoints. The robot then uses the DGPS system with an environment model for rough, high-level navigation and relies on vision and dead reckoning for localized navigation. This system is successful, and capable of navigating roads around Yamanashi University.

At Tohoku University, a system was developed to navigate a car based primarily on DGPS [13]. The car is equipped with a GPS unit, 3D scanning laser rangefinder, and ultrasonic sensors. The DGPS unit is capable of accuracies in the 5m range. The system matches the GPS coordinates with an internal 3D map for rough positioning of the vehicle's location. Because of the error inherent in the GPS, the car relies on image processing, a laser rangefinder, and shaft encoders for low level localized navigation. This system is successful in navigating predetermined courses with available accurate 3D environmental maps.

1.2.2 Aerial Vehicles

The main differences between ground-based and flight-based vehicles are the static stability and degrees of freedom of the vehicles. Ground vehicles are constrained to three degrees of freedom and are statically stable, while aerial vehicles operate with six degrees of freedom and may not be statically stable [4]. As such, GPS-based control of MAVs and other aerial vehicles presents challenges unseen in the control of ground-based vehicles.

While extensive work exists in GPS based control of ground vehicles, small investigations have been made in the control of aerial vehicles as done by S. Fürst and E. Dickmanns [5] and E. M. Atkins et al. [2]. Efforts were made at UC Berkeley to develop a navigation system for an unmanned aerial vehicle [10]. This system relies primarily on computer vision with noisy updates of its present state coming from GPS. The system architecture consists of a strategic planner, a tactical planner, a trajectory planner, and a regulation and dynamics layer. The strategic planner develops a coarse, self-optimized trajectory based on predetermined waypoints. The tactical planner makes use of the GPS and internal sensors to update the planned path based on the appearance of new obstacles. This system is still in simulation with plans for implementation on an autonomous helicopter within the BEAR project at UC Berkeley.

A navigation system for unmanned aircraft based primarily on GPS was developed at Northwestern Polytechnical University in China [14]. The system is based on either single receiver or DGPS navigation. The hardware design includes aircraft equipment and a ground station system. The aircraft equipment consists of an aircraft computer and GPS receiver. The ground station includes a GPS receiver for use in the DGPS system and a ground station computer. Unmanned flight of this system is realized using the aircraft computer with a predetermined flight plan. The base station is used only for DGPS corrections and telecontrol. This system flew successfully using a single receiver GPS.

Although the previously explained GPS based navigation systems for mobile robots, cars, and planes were successful, they were implemented on systems much larger than the MAV scale planes that are the focus of this thesis. The closest system resembling the navigation system to be implemented on MAVs was the unmanned aircraft developed at Northwestern Polytechnical Institute [14]. The payload capacity of the plane enabled an 8098 microcomputer to be flown with the GPS. Presently this is not possible given the payload capacity of MAVs. For the system we are developing, all of the computing will have to be done off-board.

1.3 Overview

In this thesis we describe the GPS-based navigation system we have developed and tested on MAVs. Chapter 2 introduces MAVs and the current vision-based navigation system used for flight control. Chapter 3 discusses the hardware and software design of the GPS system and implementation on the MAV and base station. Chapter 4 describes flight tests of the system and illustrates examples of ground-based tests. Finally, chapter 5 offers some concluding discussions and thoughts for future work.

CHAPTER 2
OVERVIEW OF SYSTEM

2.1 Introduction

The original development of a MAV stability control system focused on a computer vision approach. This system was developed to address the problems associated with current sensor technology, and conserve weight and payload volume to accommodate the needs of smaller MAVs. The system was inspired by the biological MAV counterpart, the bird. In studying the nervous (control) system of birds the general observation is that birds rely heavily on sharp eyes and general vision to guide almost every aspect of their behavior [4].

An initial effort to develop a rudimentary form of vision control for flight was done by a University of Florida student, Gabriel Torres. He demonstrated using Cadmium Sulfide cells to sense the general orientation of the horizon on a television monitor. Later work was performed by a University of Florida student, Scott Ettinger, to develop a horizon tracking system using the onboard surveillance camera. This system was successful and was capable of sustained flight through video noise and sky and ground color variation due to varying weather conditions. It became the current MAV vision-based navigation system.

2.2 Micro Air Vehicle Design

In developing MAVs we again study the biological MAV counterpart, the bird. Most large winged aircraft are designed with rigid fixed wings to avoid catastrophic failures due to structural dynamics. Birds on the other hand do not have rigid wings, and instead exhibit a great deal of flexibility in their wings. The design of MAVs makes use of this flexible wing design to produce a passive mechanism called adaptive washout to suppress wind gusts’ effects on their stability. To implement this flexible wing concept, we make use of carbon fiber construction techniques to produce lightweight durable aircrafts.

The planes developed for use in this thesis have wingspans from 24in to 5in. For initial tests, a 24in MAV will be used since it has the highest payload capacity. The 24in plane is capable of carrying 150g in addition to its primary flight systems including servos, a motor, receiver and batteries. Using a standard configuration, the MAV is capable of sustained flight for up to 45min. This flight time is essential for close range surveillance missions.

2.3 Vision System

The vision-based system takes advantage of the surveillance capabilities of MAVs. With a color camera and transmitter already included in the payload, the system does not rely on any additional payload to control the MAV. All the vision-based control work is done off-board using a base station computer on the ground.

The vision-based system derives its control using a direct measurement of the aircraft's orientation with respect to the ground. The two degrees of freedom critical for stability in this measurement are the bank angle (Φ) and the pitch angle (Θ). These two angles are determined directly from the horizon estimate of an image from a forward facing camera on the aircraft. The bank angle is determined as the inverse tangent of the slope of the horizon line. The pitch angle is estimated to be closely proportional to the percentage of the image above or below the line.

The horizon estimating algorithm is based on the assumption that the sky and ground sections of the image are distinctly different in color and texture, and the horizon can be approximated by a straight line separating these two regions. Using this approach, the algorithm becomes the task of fitting two polygons to the sky and ground regions of the image as in Figure 2-1. The horizon line separation is used to determine these polygons for a statical modeling technique

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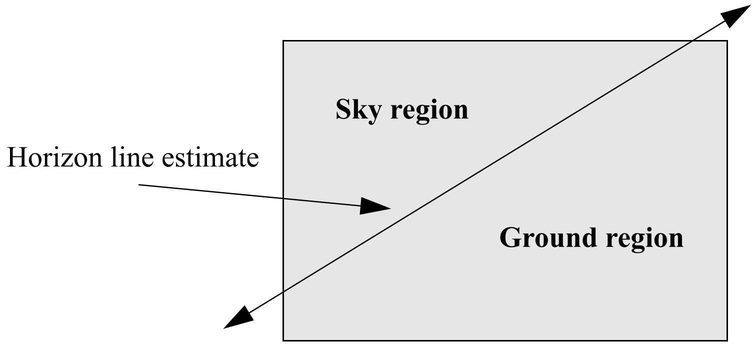
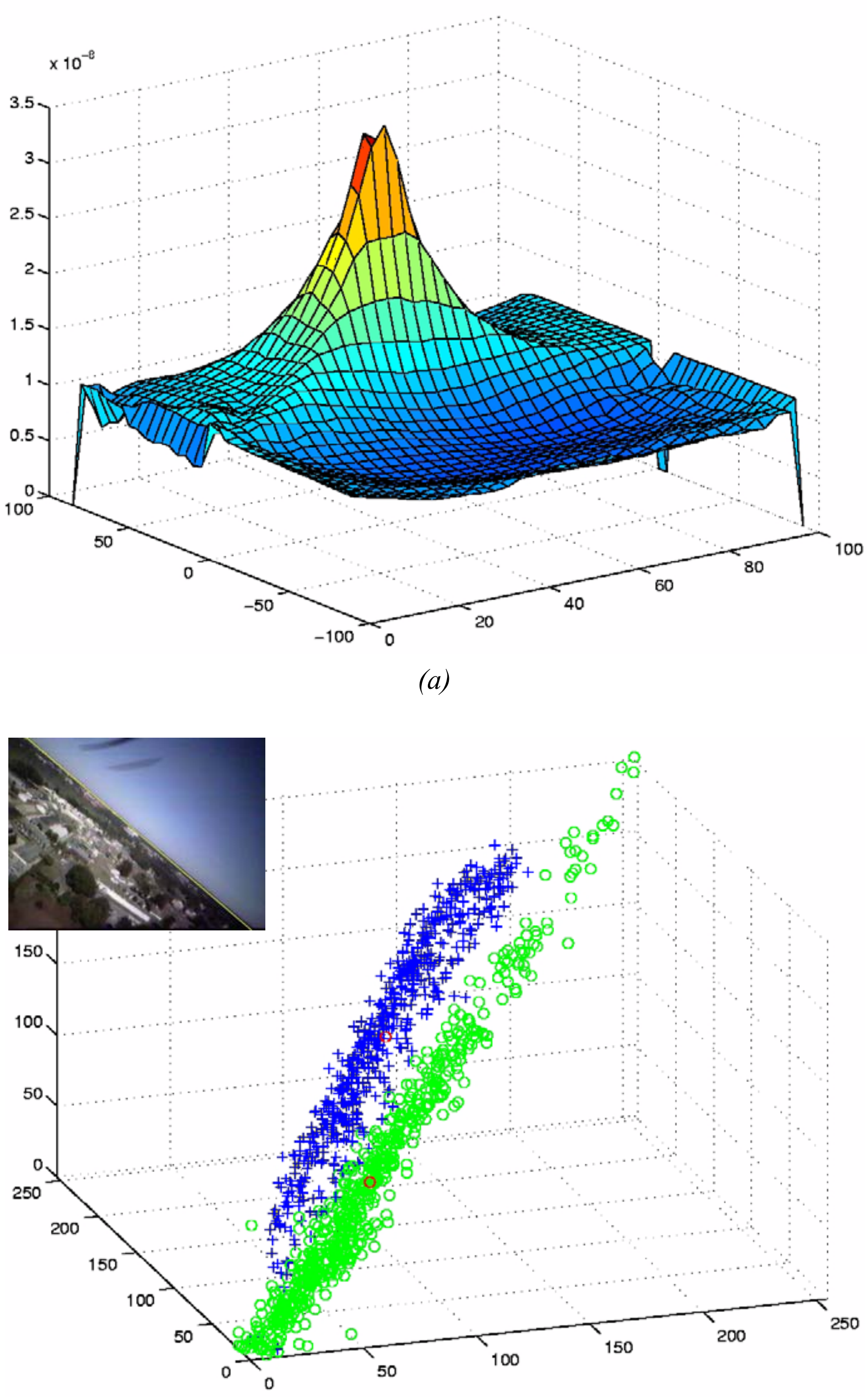


Figure 2-1: Polygon estimation using horizon line separation

The horizon estimation algorithm begins with a course search of the image, fitting horizon estimates based on previously defined search parameters. The various sky and ground regions resulting from this search are modeled as a Gaussian distribution in RGB space. Using the Gaussian model, the mean and covariance matrices of the two distributions are calculated and used in the cost function equation (2-1), where Σ_G denotes the covariance matrix for ground pixels, and Σ_S denotes the covariance matrix for sky pixels. This cost function is used for computing the line with the highest likelihood of being the best-fit horizon.

$$F = [|\Sigma_G| + |\Sigma_S| + (\lambda_{G1} + \lambda_{G2} + \lambda_{G3})^2 + (\lambda_{S1} + \lambda_{S2} + \lambda_{S3})^2]^{-1} \tag{2-1}$$

A typical fitness function surface is shown in Figure 2-2 (a), while Figure 2-2 (b) illustrates the distribution of sky pixels (blue crosses) and ground pixels (green circles) in RGB space. Locating the best-fit horizon line search becomes a task of finding the global maximum on the fitness surface.



(a)

(b)

Figure 2-2: Horizon estimation; *(a)* Fitness surface; *(b)* pixel distribution in RGB space

Once the system has identified the most likely estimate of the horizon, Φ and Θ are determined using the previously explained methods. The next stage in the navigation system uses these pitch and bank estimates in determining the proper actions to fly the MAV. The system takes input from the user via joystick control for the user desired horizon location. This desired horizon is compared with the estimated real horizon and the resulting error function is calculated.

The flight control surface settings are determined from a controller operating on the horizon error function. The proper locations of the flight control surfaces to achieve to the desired horizon location are calculated in this controller. These locations are transmitted to a receiver on the MAV through servo control commands directly from the computer, completing the control loop in Figure 2-3.

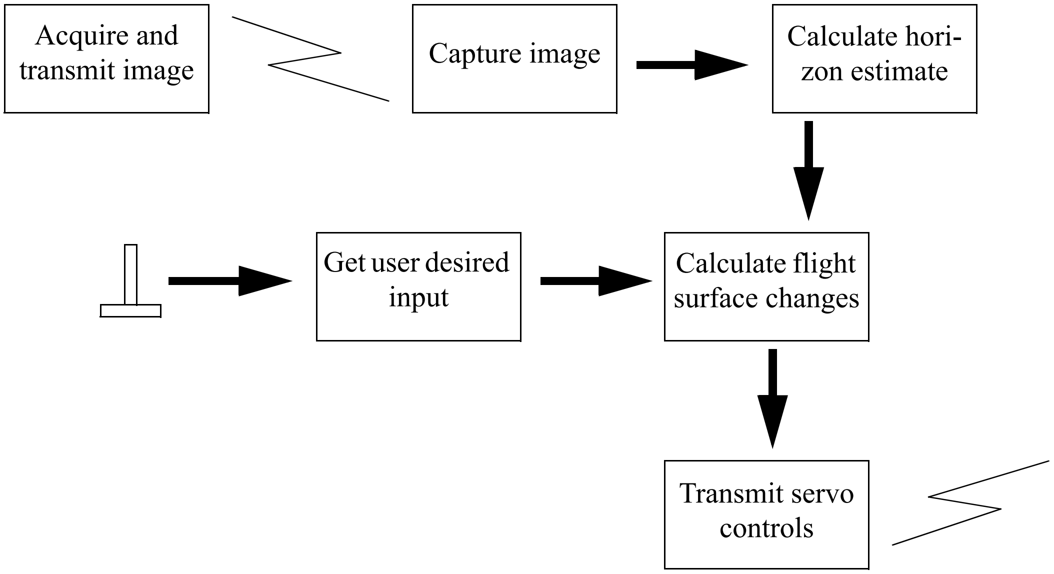


Figure 2-3: Vision-based system control diagram

2.4 Control Limitations

The vision-based navigation system proved to be a useful tool in allowing unskilled pilots to fly a MAV. While the vision-based system is capable of flying through rudimentary human control, the goal of this thesis is to produce a fully autonomous navigation system for MAVs. This is not possible using only the current vision-based system. A new GPS-based navigation system will have to be added in addition to the vision-based system to achieve fully autonomous flight capable of navigating a predetermined course.

The current vision-based navigation system is capable of controlling the pitch and bank angles of the MAV. While this is necessary for controlled level flight, it only produces low-level navigation. The system was designed to rely on user input for high-level navigation. The user is responsible for controlling the aircraft’s location, namely altitude, latitude and longitude. By implementing a GPS-based navigation system we can eliminate the need for human interaction, and instead rely on the GPS for measurements of altitude, latitude and longitude. In addition to the primary navigation measurements, GPS can provide us with measurements of ground speed and course.

It is possible to determine the primary navigation measurements through the vision system using optical flow analysis. This system would determine such things as speed, course and location through estimates of pixel movements in an image. While this would achieve the goal of producing a minimal payload system by not adding additional hardware to the MAV, it would not be as accurate as the GPS. The optical flow analysis system would be much more computationally intense needing faster computers, and would not be easily deployable. The current surveillance systems on the MAVs produce low quality noisy images possibly rendering any optical flow analysis system useless.

The vision-based system uses a forward facing camera mounted on the MAV. These cameras can become shaken during or even before flight. The vision system is unable to account for the off-center camera, and relies on a level forward facing image. If this image becomes twisted due to flight or improper placement, the level horizon will not lie on the center line of the image. This will cause the navigation system to constantly bank, climb, or dive to achieve a level horizon in the image leading to unstable flight. The GPS-based system can account for an unlevel image through high-level navigation measurements. These corrections can be fed into the vision-based system producing, a more robust navigation system.

CHAPTER 3
LIGHT-WEIGHT GPS NAVIGATION SYSTEM

3.1 Introduction

The integration of GPS navigation into the MAV control system consists of developing a hardware and software layer. When designing the hardware system we must consider the payload requirements of the MAV. This requirement is the main restriction as to what processing will be done on the MAV and on the ground, and what hardware will be used in the MAV. Therefore, the hardware system will consist of an on-board and off-board component.

The on-board hardware will enable the system to directly determine the GPS coordinates of the MAV using a GPS receiver and antenna mounted on the MAV. This system will not perform any navigation processing, and will only be used to gather data. The system will be responsible for collecting GPS data and transmitting it to the base station. The base station hardware will be responsible for receiving the GPS data transmissions and making them available for use in the computer.

A software control system is needed on the base station to extract the GPS data from the MAV and determine the current flight path and new flight controls. The vision-based system currently uses a base station computer to process data from the video camera and produce flight controls. It was determined that the GPS-based system should use the same base station computer as the vision system to enable ease of integration, and limit the amount of additional hardware.

3.2 Hardware Description

To meet the small payload requirements of the MAV, we searched for a small lightweight GPS receiver with standard functionality and limited user dependence. To satisfy these requirements, we used the *Royaltek REB-2000* GPS receiver. This unit is an 11-channel GPS receiver transmitting NMEA update messages at 1HZ through a local serial port. The unit operates on 3.3V at less than 170mA, and weighs 8.6g. The weight of this receiver falls well within the payload requirements of the MAV.

The documented error of the GPS receiver is in the range of 15m. The typical observed drift is around 7m to 10m. These error measurements might seem too large for raw navigation purposes, however, they are within control limits. The MAV must maintain considerable speed to stay airborne for proper operation. The average speed during test flights is around 40mph to 50mph. This amounts to around 20m of ground coverage per second. With GPS data updating at 1Hz, the drift due to error becomes tolerable since the MAV will always be outside the range of error by the time the next data set arrives. While this is not precise navigation, it is sufficient for following a general flight path.

An equally small GPS antenna was needed to interface with the GPS receiver. When shrinking the size of a passive GPS antenna, signal degradation becomes large, and it is difficult to produce usable satellite transmissions. We determined we would need an active antenna with a sizable gain that consumes minimal power. The GPS antenna that meets our requirements is the *Tri-M Micro Skymaster*. This antenna has a 24dB gain with a maximum of 12mA current consumption. The antenna interfaces directly to the GPS receiver through a MMCX right angle connector. For the purposes of this thesis, the antenna cable was shortened from 3ft. to 14in to reduce extra payload.

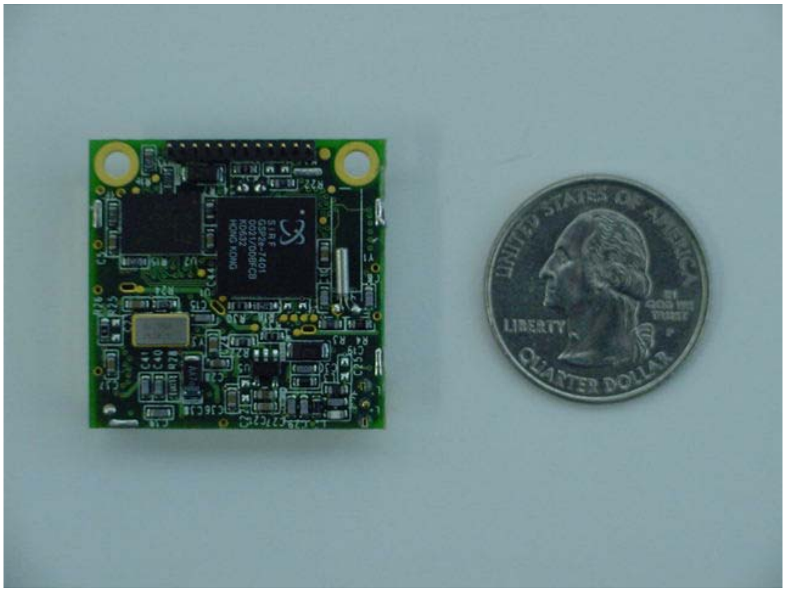


Figure 3-1: *REB-2000* GPS receiver

To enable the base station to receive the serial NMEA messages from the MAV GPS hardware, a data transmission system was needed. An appropriate baud rate should be around 4800 Bps to conform with the standard NMEA transmission protocols. The system should also satisfy the inherent MAV qualities of long range, low weight and low noise succeptability. A low power system was also desired to maximize battery life.

To satisfy the data transmission requirements, a system was designed using the *TX1\RX1* FM serial data transmitter/receiver pair designed by *Radiometrix*. These units operate on the 173.25MHz FM band and can transmit at data rates up to 10 KBps. The overall range of the system can approach 10Km with the proper antennas and data rate. The *TX1* and *RX1* operate at 3.3V, and have internal regulators. They consume 10mA on average. These properties of the *TX1/RX1* make them suitable for use in MAV applications.

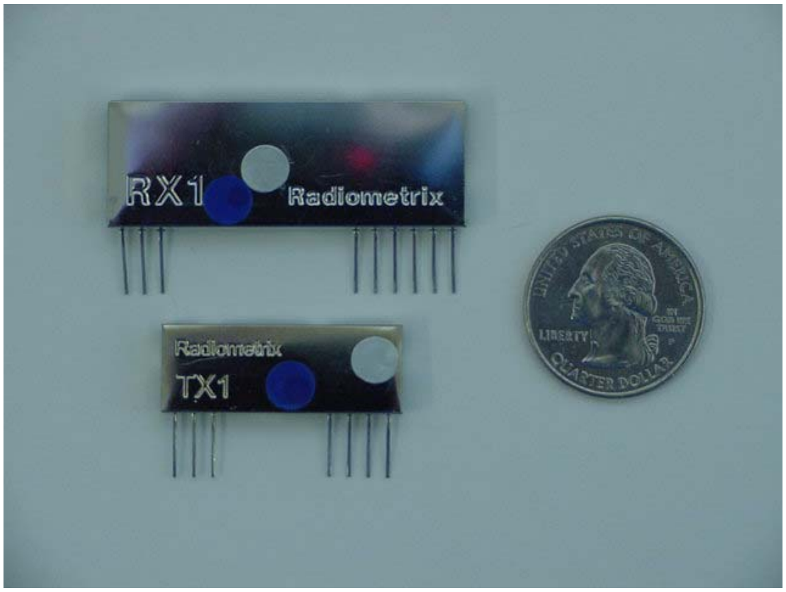


Figure 3-2: *Radiometrix TX1 RX1* FM data transmitter receiver pair

The *TX1* FM data transmitter unit was interfaced directly to the *REB-2000* GPS receiver as shown in Appendix, Figure A-3. The receiver boots up with a default data rate of 9600 Bps. While the data transmission system is capable of this high data rate, it is not suitable for use over long ranges. A system was developed to directly interface to the GPS receiver and initialize it to send the NMEA update messages at 4800 Bps, lowering the data rate of the FM data system, thereby increasing the possible range. This system was mounted on the MAV with the GPS antenna and data transmit antenna, adding a total of 57g to the MAV payload.

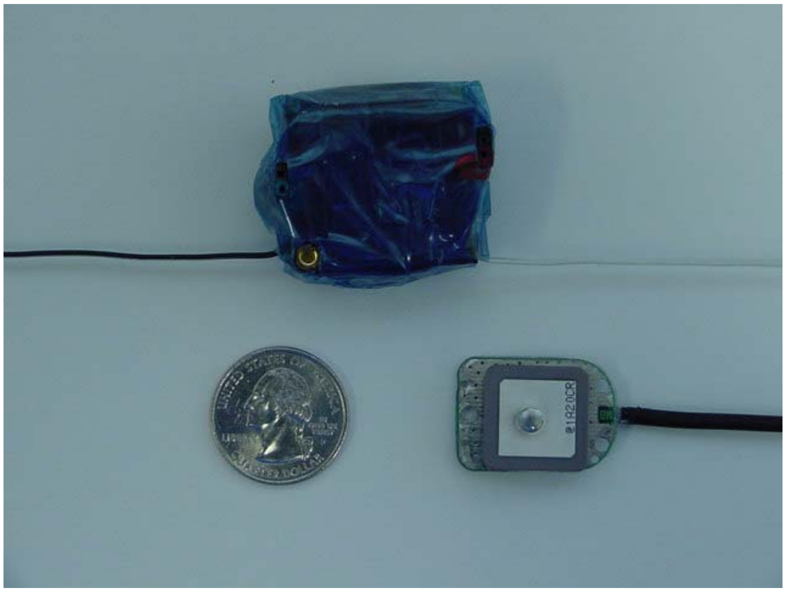


Figure 3-3: Complete GPS on-board navigation package

To help improve the transmitted signal quality and range, a variety of transmit antennas were experimented with. To meet the MAV payload restrictions, we decided to use a simple low-gain antenna system on the MAV. While this system might limit the transmit quality of the data, it is necessary to maintain the flight characteristics of the MAV. To ensure long range data transmission would be possible with this limited transmission antenna, we decided the base station should use a large high-gain antenna since there are no weight restriction on the ground.

The first antenna used on the MAV for data transmission was a quarter wave whip antenna made from 20 gauge wire. The quarter wave antenna produced insufficient results due to the lack of an appropriate ground plane. The best possible antenna that satisfies the weight restrictions of the MAV and produces better transmission characteristics is a half-wave antenna. This antenna consists of a quarter wave signal antenna and a quarter wave ground antenna attached on the leading edges of the MAV's wings. While the antenna is not extremely powerful, it is capable of long range transmission. If an appropriate powerful antenna is used on the base station, the strength of the transmission antenna is not extremely important.

The base station was designed to enable the computer to receive the transmitted NMEA messages from the MAV GPS receiver. The *RX1* FM data receiver was interfaced to the computer's serial port, thereby allowing the machine to receive GPS data from the MAV, as shown in Appendix, Figure A-1. The system was designed to use a 5/8 wave omnidirectional whip antenna to maximize the receive strength of the base station while not limiting the antenna position.

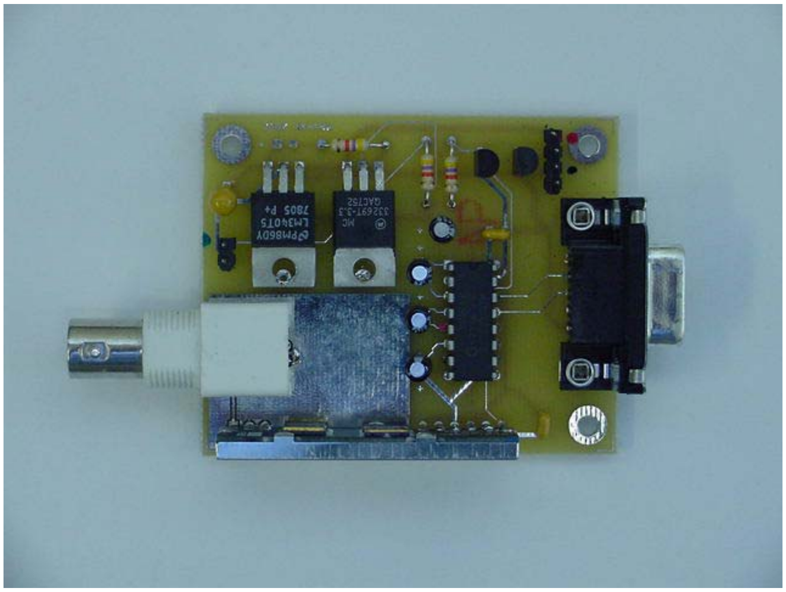


Figure 3-4: FM data receiver board

3.3 Software Description

The software package for the GPS-based navigation system consists of three main control structures: (1) data input and extraction, (2) control system and (3) vision system interface. These systems interact to gather data from the GPS receiver on the MAV, determine proper flight control changes to achieve the desired mission goals and interface with the current vision system. The software is based on the flow diagram in Figure 3-5.

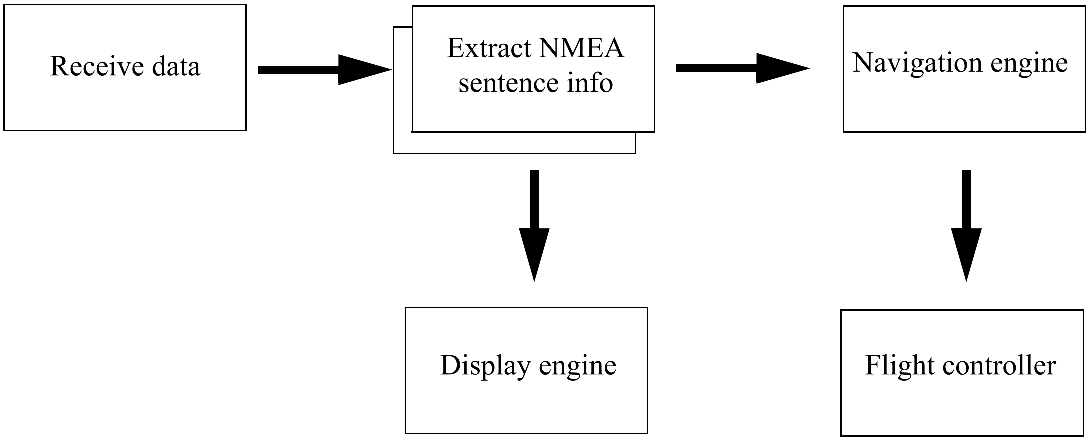


Figure 3-5: Software flow diagram

The data input and extraction system is the first step in the program flow. The system is designed to directly interface with the GPS receiver and the base station data receiver. The GPS receiver is initialized to transmit NMEA GPS sentences at 4800 Bps with a 1Hz update frequency. The data input and extraction software reads these NMEA sentences from the RS-232 port and decodes them for use in the other parts of the software package. The system is extremely robust to account for invalid data due to signal degradation when flying at large distances from the base station.

Included in the data input and extraction system is the data display console. This section provides the user with all the data transmitted from the GPS receiver, as well as the current navigation data being used in the flight control system. It also enables the user to make changes to the flight path on the fly.

The software control system is the next step in the program flow. This system first takes the raw GPS data and converts it into the proper units for use in the flight controller. It then uses the desired flight plan to determine the necessary navigation controls for achieving autonomous flight.

The flight plan consists of a number of waypoints for the MAV to traverse. The user designs a course based on latitude, longitude and altitude measurements at discrete points on the path.

The system is designed around a central PID controllers based on the PID control equation

$$m(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \tag{3-1}$$

and uses two individual PID systems to control the direction, or bearing, and the altitude. The errors for the PID system are determined from the current GPS position data and the predetermined flight plan. The altitude is taken directly from the GPS GPGGA NMEA sentence. The position and course data are taken from the GPS GPRMC NMEA sentence. The bearing controller is updated using the error between the current bearing to the desired point and current course as shown in Figure 3-6. The altitude controller is updated using the error between the current and desired altitude. The proportion (K_p), integration (K_i) and differentiation (K_d) constants were tuned all tuned by hand during tests.

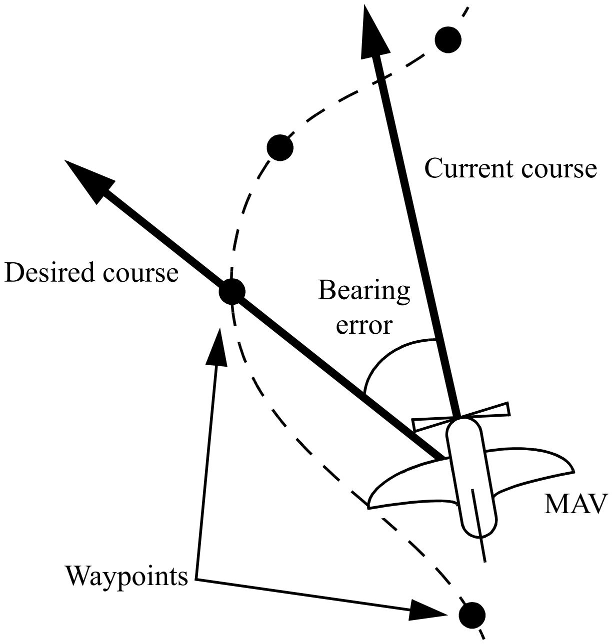


Figure 3-6: Flight path bearing error illustration

The bearing error is based on the current course and the bearing to the next requested waypoint in the predetermined flight path, and is calculated using the Great Circle equations for navigation in a three dimensional environment. The bearing to the next requested waypoint is calculated by first determining the distance to the next waypoint using equation (3-2). This distance is used in equation (3-3) to determine the absolute bearing off north. The resulting bearing is used as the desired bearing in determining the PID error measure [11].

$$d = \operatorname{acos}(\sin(lat_1) \cdot \sin(lat_2) + \cos(lat_1) \cdot \cos(lat_2) \cdot \cos(lon_1 - lon_2)) \tag{3-2}$$

$$c = \operatorname{acos}\left(\frac{\sin(lat_2) - \sin(lat_1) \cdot \cos(d)}{\cos(lat_1) \cdot \sin(d)}\right) \tag{3-3}$$

The final phase of the program flow is the vision system interface. The vision system was designed around user input to determine the desired pitch and bank angles. Without user input the system would continue to fly on a level straight course. The GPS vision system interface take the place of the user input.

The interface provides the desired pitch and bank angles based on the GPS system PID controllers. The control output from the altitude PID system is used in determining the desired pitch percentage for the vision interface. The control output from the bearing PID system is used in determining the bank angle for the vision system interface. The vision system uses the desired GPS pitch and bank angles in the main flight controller to determine the proper control surface changes. This enables the system to maintain the main flight control interface in the vision system for ease of integration. It also allows the vision system to continue legacy support for user input when GPS is unavailable. The new navigation system resulting from the integration of the legacy vision-based navigation system and new GPS-based navigation system is illustrated in Figure 3-7.

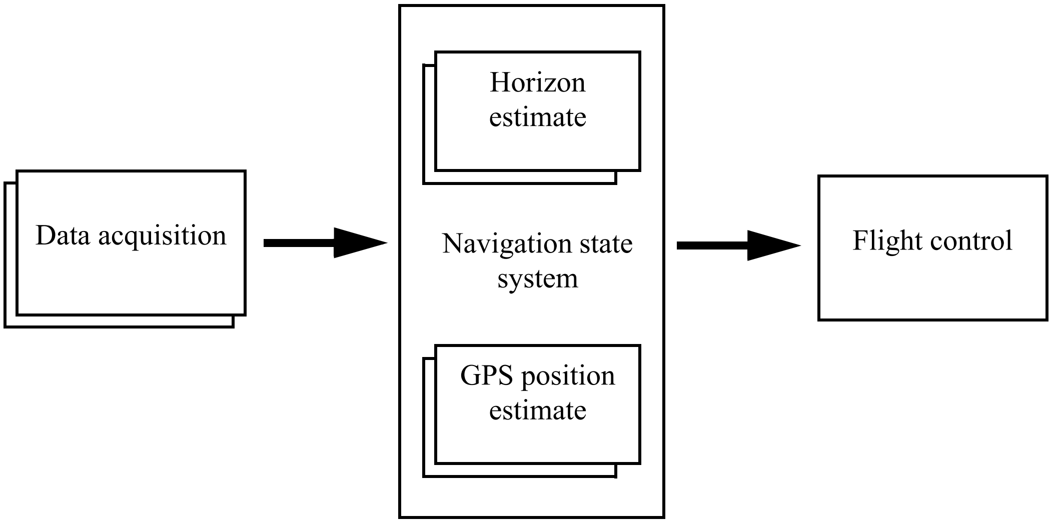


Figure 3-7: Vision-based navigation and GPS-based navigation system integration

The system was designed and assembled based on the specifications defined in this chapter. Schematics illustrating the hardware design are given in the Appendix. Each sub-system was developed independently and tested for validation. When completed, the navigation system represents a complete control loop for autonomous navigation of a MAV based on computer vision and GPS with limited additional payload.

CHAPTER 4
EXPERIMENTAL RESULTS

4.1 Introduction

With the hardware and software layers complete, we began testing of the individual components before integrating the entire system. We began by testing the feasibility of the GPS system based on the accuracy of the GPS data. This focused mainly on the positional errors inherent in the standard positioning service. Next, we tested the hardware capabilities. The GPS receiver was checked for valid data and the data transmission range was tested. This was performed by building a MAV designed for large payloads, and installing the GPS hardware. The MAV was then flown to test the transmission range. After all the individual systems were working within specifications, they were integrated to test the autonomous navigation capabilities. The high-level control systems were calibrated and tuned resulting in a system capable of autonomous flight based on a predetermined course of waypoints.

4.2 Initial Testing

Initial testing of the GPS receiver did not yield suitable results. It was determined that the antenna cable shortening was unsucessfull. The amplified antenna is designed to drive at least 3ft of cable. With the cable shortened, the signal amplifier would cause noise interference in the GPS receiver. To counter this problem, we replaced the active antenna with a passive L1 substrate. This antenna is not amplified and is designed for short length cables.

To test the accuracy of the GPS data and the data logging software, we performed an experiment with the GPS unit in a car. We attached the receiver to the car, and drove along streets at the University of Florida. We logged various waypoints along the path producing the map overlay in

Figure 4-1. The errors in the path/road match up in Figure 4-1 are mostly due to inconsistencies in the map, however, GPS positional errors play a small role. This initial test proved GPS can be used with the hardware and software design to produce accurate navigation measurements for the MAV. The errors shown in this test are within the range necessary to produce autonomous flight.

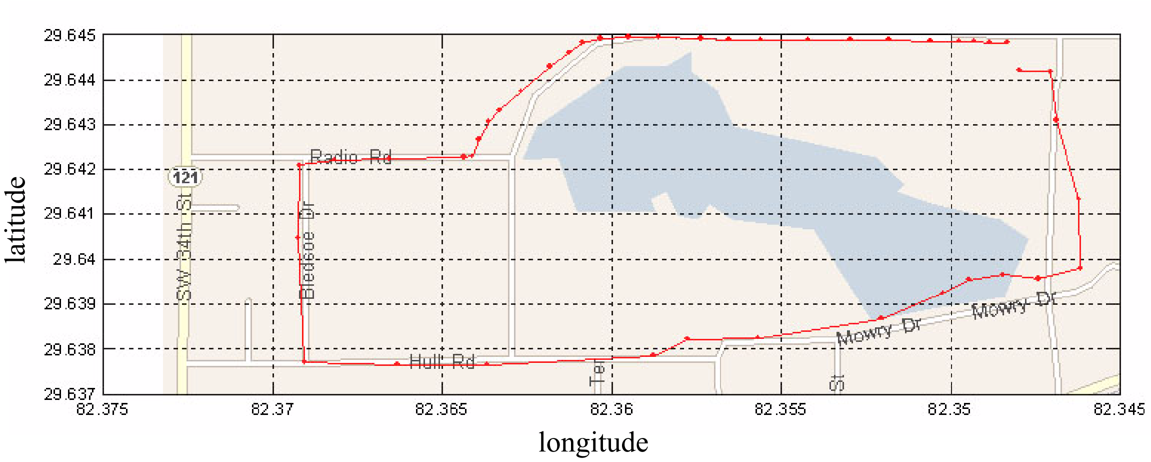


Figure 4-1: GPS data from test path with map overlay

The next phase of testing called for a check of the communication abilities between the GPS receiver, the video transmitter and the base station computer. This requires developing a high payload capacity MAV on which to instal the GPS unit. The MAV developed for this and all future flight tests, shown in Figure 4-2, is based on the TooGruven wing design produced in the MAV laboratory at the University of Florida. It has a 24in wingspan with a payload capacity of 150g in addition to servos, a receiver, a motor and batteries.

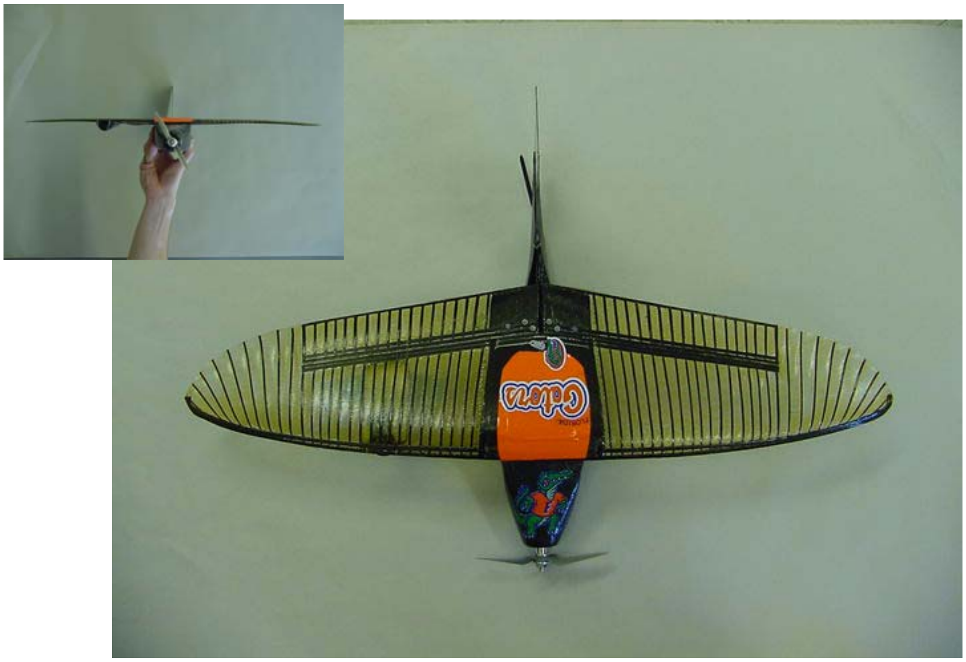


Figure 4-2: MAV developed for flight tests of navigation system

The camera, used for general surveillance and the vision-based navigation system was traditionally placed on the tail of the MAV. While this placement produced usable images, it was directly in-line with the propeller. Depending on the arrangement of the tail, the propeller would appear in the top or bottom regions of the image. This is not a problem when used for general surveillance, however, it does affect the horizon identification algorithm. The propeller changes the pixel distribution of the sky and ground regions, resulting in some false horizon estimates. For this reason, the camera was placed under the wing, out of the way of the propeller, as seen in Figure 4-2

The GPS unit was installed on the MAV with the half wave antenna placed along the leading edges of each wing to reduce drag. The GPS receiver antenna was placed on the top of the front-end of the MAV behind the propeller. The MAV was flown in a large field at varying altitudes and distances to simulate aspects of an autonomous mission. Close range tests of the system demonstrated superior communication abilities. Longer range tests produced the same superior results not seen in the original laboratory tests. The actual data was not nearly as noisy as expected with practically no transmission errors.

The GPS unit was capable of transmission throughout the entire range of testing. The limiting factor in the navigation system was shown to be the video transmission unit. The range of the GPS data transmitter is well beyond the range of the video transmitter. This system will fail to produce a valid image well before the GPS system fails. Transmission of GPS data was even possible outside the range of the servo controller.

With all the individual hardware and software systems working within specifications the autonomous navigation system was put into place for testing. Initial lab tests were performed to test the navigation capabilities of GPS while the legacy vision-based system was controlling the MAV. The test was setup with the GPS-based navigation system receiving data, while the vision-based system tracked the horizon and received user input via joystick. The GPS-based system would suggest fight controls to the user. These suggested controls were not processed by the main navigation system and were only used for testing.

This trial run showed the improved capabilities of the navigation system when integrating the GPS-based system. With a properly tuned controller, the GPS-based system is capable of eliminating the need for user input to navigate a predetermined path. The system will be able to provide control updates equal to or better than a human.

4.3 PID Controller Tuning

With all the systems integrated and tested, the PID control element of the GPS-based system was to be tuned. The difficulty in tuning this controller is the potential for a catastrophic crash due to non-dampening control. The MAV can not be flown directly by the autonomous navigation system until this controller was properly tuned, however, tuning the controller requires flying the MAV.

Initial trials for tuning the PID controller were performed in simulation in the laboratory. A fixed set of waypoints were arranged at various locations around the laboratory. The flight control system was run with the GPS receiver stationary on the roof. We would observe the controller's actions for maintaining stable flight, and attempt to correct the PID controller based on our observations.

These initial tests of the PID system exhibited the difficulty in tuning the gains of the controller. We would need to develop a system capable of indirect control of the MAV. This system would suggest flight controls to the user while not actually controlling the plane. The user could then observe these suggestions, and update the PID gains as necessary.

To properly tune the PID system while maintaining stability of the MAV, we developed a process where a pilot would fly the MAV through a predetermined course using the vision-based system and the joystick. The GPS-based system would suggest a horizon position based on the course, as shown in Figure 4-3. Observations would be made as to the instability of the PID system, and the proper changes would be made. The system would then be reset to observe the changes.

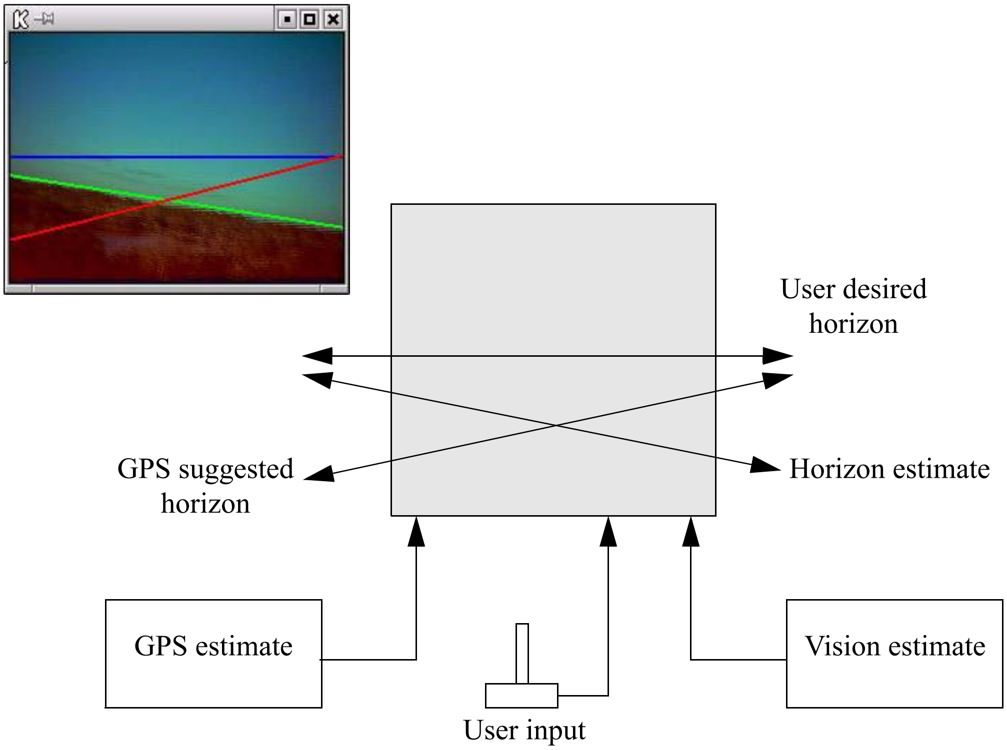


Figure 4-3: PID controller tuning method

Tuning of the PID system using this method will not be as difficult as initially expected. Slight changes to the gain values should result in a suggested horizon location similar to the user's input. As long as the output values of the PID controller are within the range of joystick values the system can not become unstable. This is due mainly to the original design of the flight controller, which was based solely on user input.

The specifications of the flight controller enable any pilot to indirectly fly the MAV. The pilot's input, while used as the basis for navigation, is not allowed to cause instability in the MAV's flight. These same specifications are used when processing GPS suggested horizon locations. If the GPS desired navigation updates cause any instability in the MAV's flight, they will be ignored until stable horizon locations are achieved.

4.4 Ground-Based Testing

After the PID system was tuned to produce horizon location suggestions within specifications, the waypoint navigation system was tested. Various courses were selected to test the different aspects of the MAV's navigations capabilities. The courses ranged from one to four waypoints. Some problems with the navigation system were discovered during these tests and corrected for later tests.

The first test was based on a course of four waypoints arranged in a square pattern around the testing area with a constant altitude. The MAV was moved, by hand, along the course on the ground. This data arrangement would allow us to observe the system's response to sharp 90° turns and long straight paths.

The navigation system produced unexpected results in this test. After the navigation system gained control, horizon location suggestions forced a turn in the direction of the first waypoint. Once the area around this waypoint was reached, the system began to react erratically, suggesting sharp left and right turns. We immediately halted the navigation system to determine the cause of the erratic control.

Investigations into the high-level control strategies revealed erroneous assumptions that could account for the chaotic control observed. The navigation system maintains a list of the waypoints to traverse with a holder for the current desired location. The system will not change the current desired location to the next waypoint until the current waypoint has been registered in memory. Given the speed of the MAV, the GPS positional errors and the GPS data update frequency, there is a small likelihood that the current desired waypoint will be registered. The system will most likely fly the MAV past the current desired waypoint and make immediate sharp turns in an attempt to reverse the MAV. This might result in the MAV flying in a circular pattern around the waypoint without ever reaching it. This error is the possible cause for the sudden erratic control observed during the previous test.

To correct for the single-point navigation assumptions, a new control state was added to the navigation control loop. As before, the system will maintain a flight path towards the current desired waypoint, however, the rule for deciding whether the desired waypoint has been achieved will be different. The waypoint will be changed once the MAV has penetrated an area around the waypoint. The navigation system will continually check the distance from the current location to the desired waypoint to determine if the MAV has penetrated the area, as shown in Figure 4-4. This will allow for the various data discrepancies discussed above while traversing a general course. The MAV is not required to pass over the actual waypoint in this strategy.

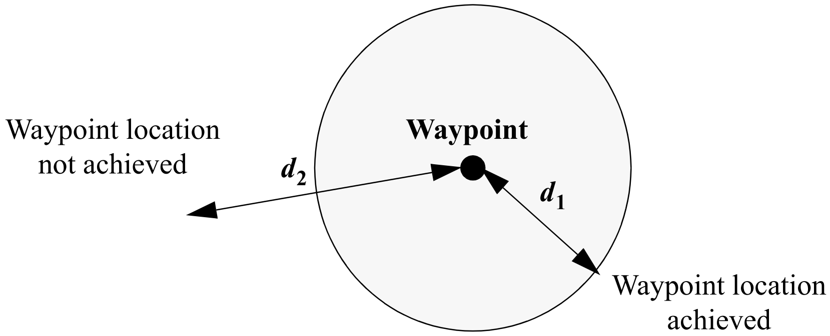


Figure 4-4: New waypoint navigation method

With the navigation software updates in place, a second flight test was attempted based on the course used in the first test. The navigation system immediately suggested a heading to follow a direct course to the first waypoint. After passing through the area surrounding the waypoint, the system suggested a turn to move to the next waypoint. The system continued in this fashion, eventually traversing all four waypoints.

Additional tests were performed to check various mission complexities. Desired altitudes were set at different levels throughout the tests. The number of waypoints in the course was also increased, resulting in wider more complex courses. In each of the tests, the system achieved the flight goals necessary to seemingly produce stable autonomous flight.

The tests discussed in this chapter exhibited the capabilities of the autonomous navigation system. While computer controlled flight was limited to ground-based simulation on simple paths, it set the basis for a higher-level system. A successful system is now in place to enable the MAV to perform a variety of autonomous missions while airborne. A pilot is only needed for take-offs and landings.

CHAPTER 5
FUTURE WORK AND DISCUSSION

The stability and control systems developed to meet the goals of this thesis, while successful, have only taken the first steps towards creating a fully autonomous MAV. The GPS-based flight control system was only developed to test the possibilities of autonomous flight. Due to the success of the system, MAVs can be now altered to achieve a variety of missions. The navigation system, however, can be greatly improved upon through hardware and software additions and improvements.

This thesis focused on control of the MAV while in flight. It planned for the pilot to transfer control to the navigation system after stable flight had been achieved. When the system completed the flight path the pilot would regain control of the MAV to perform a controlled landing. If the MAV navigation system is ever to be used in commercial applications, take-offs and landings should be automated, completely removing the pilot from the control loop. This implementation should only require software modifications since all the necessary navigation data is already available.

The system only made use of limited GPS capabilities. Although the limited accuracies available through the standard positioning service did not hinder the system's capabilities, they can be improved upon to produce even greater localization and navigation capabilities for surveillance and reconnaissance missions. DGPS presents the ability to achieve much smaller positioning errors. This system makes use of an additional receiver of ground based satellite signal corrections to provide accuracies down to 1m. DGPS can be implemented either directly on the MAV or on the base station. If implemented on the MAV a DGPS receiver will be added to the payload. In an effort to maintain light-weight payloads, DGPS can be implemented on the base station with the signal corrections calculated on the base station or radioed to the MAV GPS unit.

The original design for the vision-based navigation system included a base station computer because no system existed that was small or fast enough to be placed on-board the MAV. Presently, these computer systems are being developed, and will become available in the near future. These systems are expected to be faster than the original base station computer and small enough to fit in the MAV. The MAV makes use of two transmitters to send video and GPS data to the base station computer. If these transmitters are removed, the additional payload capacity and battery capacity available will be able to handle a computer system on-board the MAV. With radio interference removed from the control structure and data bandwidth greatly improved due to the removal of data transmission, the possibilities of sensors and flight control are endless.

The autonomous flight control system developed for this thesis was only designed to test the capabilities of GPS-based navigation. The system was tested using redundant parts on a large stable MAV to provide easy debugging capabilities. MAVs exist in much smaller sizes than that used for the purposes of this thesis. A smaller, lighter GPS-based system can be developed for implementation on one of these smaller MAVs. This will enable more covert surveillance abilities of autonomous flight systems.

The autonomous flight system made use of a predetermined set of waypoints as a desired flight path. The system used these points as independent goals along a flight path. No processing was performed to account for the location of future or past points. Only the current destination was used. An improved control system can be achieved by implementing path planning and curve fitting algorithms into the flight control structure. If this is implemented, the MAV will be capable of determining intermediate points along the loosely defined flight path producing smoother flight and possibly conserving energy.

The GPS-based navigation system developed for this thesis performed within the defined specifications. When included with the vision-based navigation system, the resulting system will be capable of fully autonomous flight. While GPS has been used to produce autonomous aviation, it has never been used in this capacity or on this scale. To our knowledge, these were the first tests of their kind, being completely autonomous through the use of computer vision and GPS.

APPENDIX
SCHEMATICS

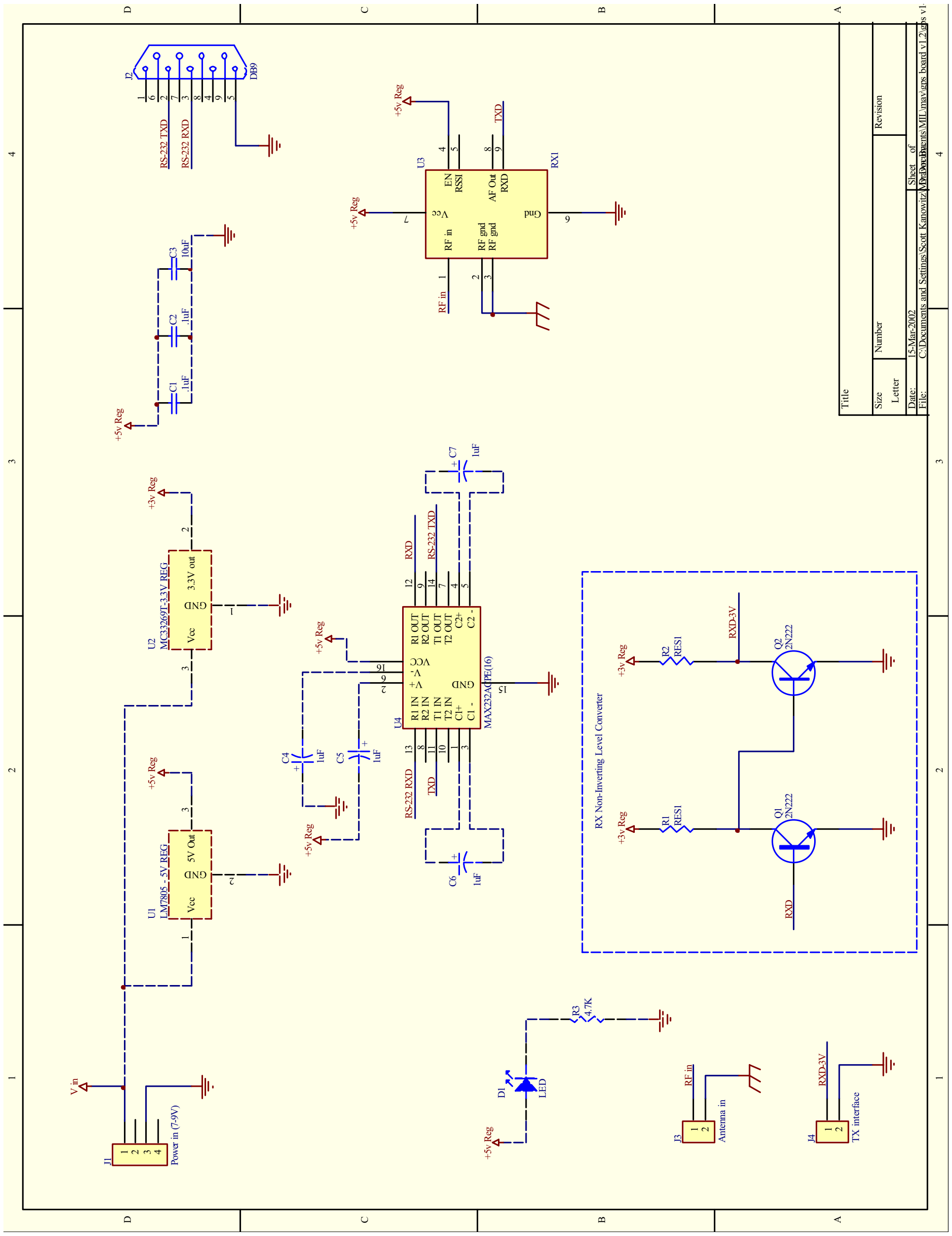


Figure A-1: Schematic for base station data receiver

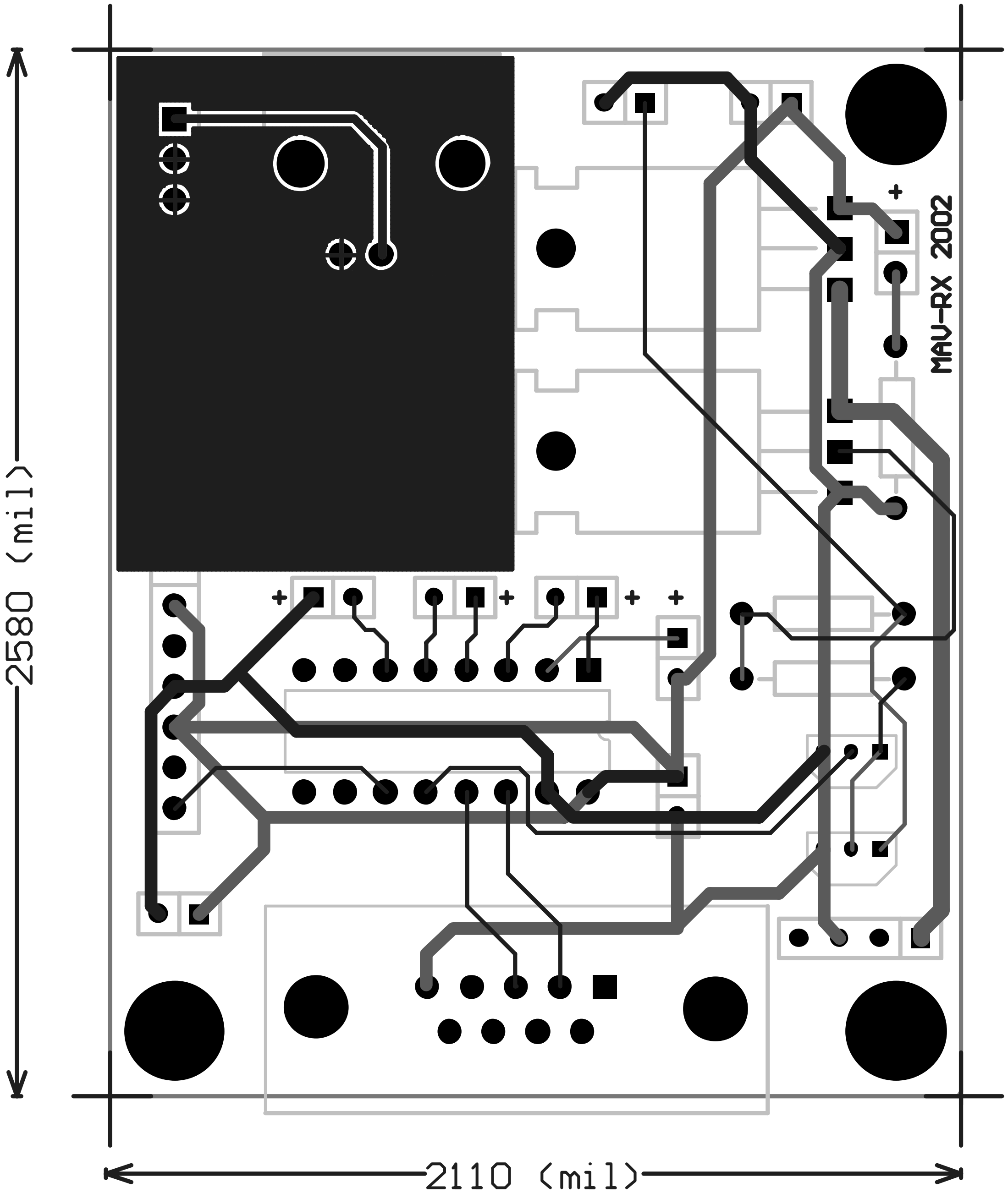


Figure A-2: PCB layout of base station receiver

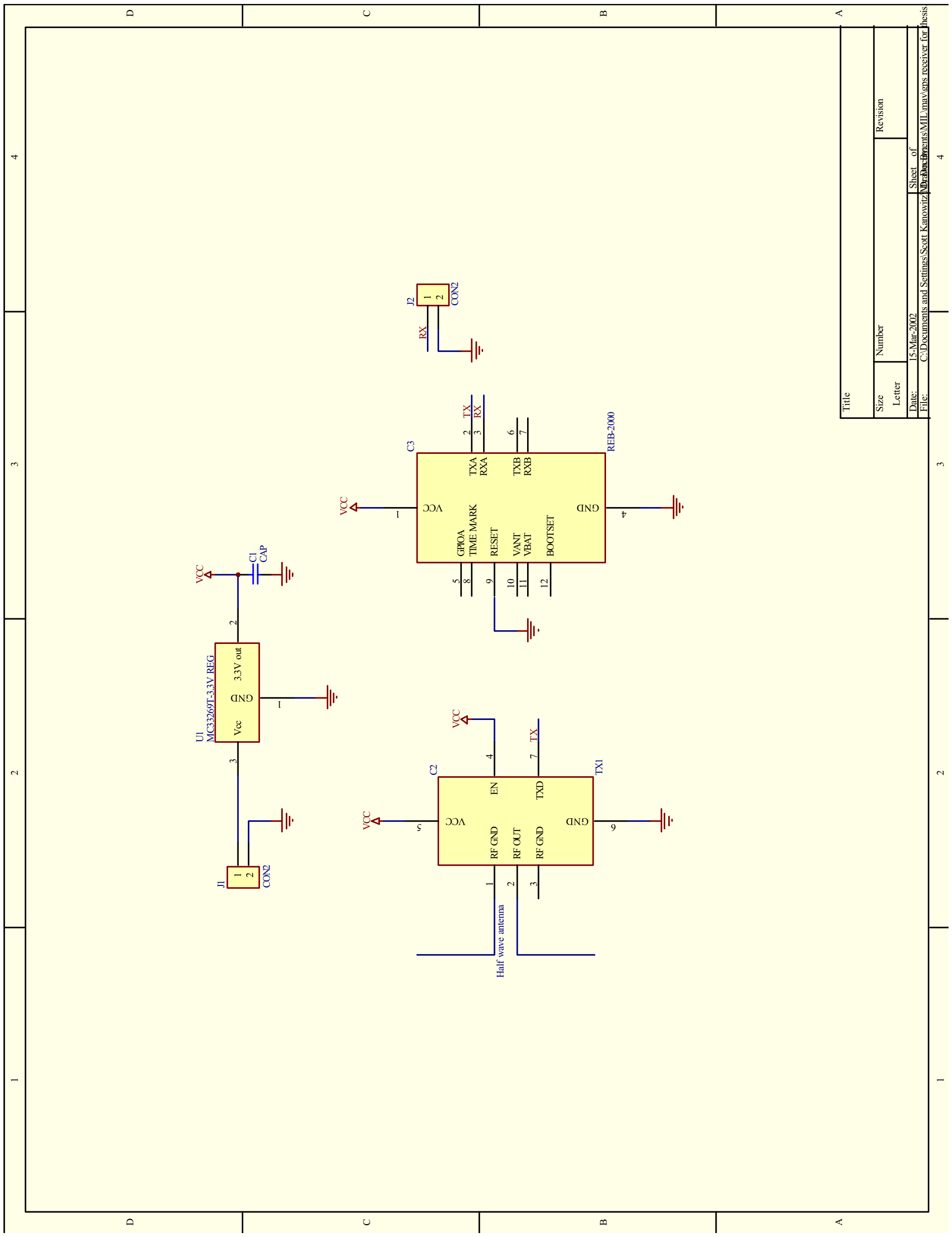


Figure A-3: Schematic for GPS receiver and data transmitter

REFERENCES

[1] M. P. Ananda, H. Bernstein, K. E. Cunningham, W. A. Feess and E. G. Stroud, “Global Positioning (GPS) Autonomous Navigation,” *IEEE PLANS '90: Position Location and Navigation Symposium Record,* pp. 497-508, 1990.

[2] E. M. Atkins, R. H. Miller, T. VanPelt, K. D. Shaw, W. B. Ribbens, P. D. Washabaugh, and D. S. Bernstein, “Solus: An Autonomous Aircraft for Flight Control and Trajectory Planning Research,” *Proc. of the American Control Conference*, pp. 689-693, 1998.

[3] M. Betke and K. Gurvits, “Mobile Robot Localization Using Landmarks,” *Proc. of the 1994 IEEE International Conference on Robotics and Automation*, Volume 2, pp. 135-142, 1994.

[4] S. M. Ettinger, “Design and Implementation of Autonomous Vision-Guided Micro Air Vehicles,” M.S. Thesis, Electrical and Computer Engineering, University of Florida, 2001.

[5] S. Fürst and E. Dickmanns, “A Vision Based Navigation System for Autonomous Aircraft,” Robotics and Autonomous Systems 28, pp. 173-184, 1999.

[6] D.A. Jenkins, P. Ifju, M. Abdulrahim and S. Olipra, “Assessment of Controlability of Micro Air Vehicles,” *Proc. Sixteenth Int. Conference on Unmanned Air Vehicle Systems,* Bristol, United Kingdom, paper 27, 2001.

[7] S. Kotani, K. Kaneko, T. Shinoda and H. Mori, “Mobile Robot Navigation Based on Vision and DGPS Information,” *Proc. of the 1998 IEEE International Conference on Robotics Automation,* pp. 2524-2529, 1998.

[8] L. Lin, T. Hancock and J. Judd, “A Robust Landmark-Based System for Vehicle Location Using Low-Bandwidth Vision,” Robotics and Autonomous Systems 25, pp. 19-32, 1998.

[9] G. Lu, “Development of a GPS Multi-Antenna System for Attitude Determination,” Ph.D. Dissertation, Dept. of Geomatics Engineering, University of Calgary, Canada, 1995.

[10] B. Sinopoli, M. Micheli, G. Donato and T. J. Koo, “Vision Based Navigation for an Unmanned Aerial Vehicle,” *Proc. of the 2001 IEEE International Conference on Robotics and Automation,* pp. 1757-1764, 2001.

[11] J. Setfan, “Navigating With GPS,” Circuit Cellar, issue 123, pp. 22-27, 2000.

[12] K. L. Van Dyke, “The World After SA: Benefits to GPS Integrity,” *IEEE 2000: Position Location and Navigation Symposium,* pp. 387-394, 2000.

[13] L. Wang, T. Emura and T. Ushiwata, “Automatic Guidance of a Vehicle Based on DGPS and a 3D Map,” *Proc. of the 2000 IEEE Intelligent Transportation Systems Conference,* pp. 131-136, 2000.

[14] Y. Wang, X. Li and Y. Huang, “Navigation of a Pilotless Aircraft Via GPS,” IEEE AES Systems Magazine, vol. 11, issue 8, pp. 16-20, 1996.

BIOGRAPHICAL SKETCH

Scott Kanowitz was born in Hollywood, Florida, in 1978. After graduating from high school in 1996, he attended the University of Florida. In 2000, Scott earned a Bachelor of Science in computer engineering from the University of Florida. He has since worked in the Machine Intelligence Laboratory pursuing a Master of Science in electrical engineering while attending the Warrington College of Business Administration to pursue a Master of Science in business management.